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A brief summary of the accomplishments and conclusions of the work by BBN include: (1) An acknowledgement scheme to improve the throughput and reduce the delay for unicast control packets was designed and implemented. Experimental results showed that acknowledgments substantially improved unicast packet throughput and delay, and consequently improvement in a mixed traffic scenario. (2) Experiments to determine the mean and standard deviation of node degree in randomly generated network topologies using MMWN's propagation and mobility model was found to be much higher than expected in small networks. Since the fidelity of the MMWN system simulation was very high, due to hardware and budgetary constraints, only small (twenty or

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A Generic Control Channel Mechanism for Mobile Multi-hop Networks

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Final Progress Report

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1 Forward

This is the final progress report of the University of Texas at Dallas Global Mobile Information Systems (GloMo) project "A Generic Control Channel Mechanism for Mobile Multi-hop Networks," funded by the United States Army Research Office USARO Award DAAG55-97-1-0312.

A major effort in this project was to demonstrate the Time-Spread Multiple-Access (TSMA) protocol as a control channel mechanism in the MMWN (Multimedia over Mobile Wireless Networks) system of our subcontractor, BBN Technologies. TSMA unifies the mobility transparency of probabilistic protocols with the guaranteed delay of deterministic protocols making it an extremely attractive for mobile networks.

A brief summary of the accomplishments and conclusions of the work by BBN include: (1) An acknowledgement scheme to improve the throughput and reduce the delay for unicast control packets was designed and implemented. Experimental results showed that acknowledgments substantially improved unicast packet throughput and delay, and consequently improvement in a mixed traffic scenario. (2) Experiments to determine the mean and standard deviation of node degree in randomly generated network topologies using MMWN's propagation and mobility model was found to be much higher than expected in small networks. Since the fidelity of the MMWN system simulation was very high, due to hardware and budgetary constraints, only small (twenty or fewer nodes) networks could be evaluated with high confidence by BBN. In these conditions, the results of the experiments showed similar performance of TSMA and CSMA when the TSMA frame length was adjusted by the worst case frame length. (3) An autonomous topology control module (ATC) developed in BBN's DAWN system became available and could be used for controlling node degree, specifically, to reduce node degree. A network using ATC matched with aggressive TSMA schedules shows considerable promise as a strong solution for smaller networks.

The University of Texas at Dallas evaluated TSMA as a medium access control (MAC) protocol, i.e., for the transmission of data packets. The high fidelity MAC layer simulator included a mobility model that guaranteed no node would exceed a specified node degree. Under these circumstances, TSMA was shown to outperform Aloha, Slotted Aloha, non-persistent CSMA, TDMA, MACA and IEEE 802.11 at high load. These results greatly support the use of ATC in smaller networks. As well, a MAC layer TSMA model was contributed to the GloMoSim library, thereby also permitting its use in SEAM-LSS.

The University of Texas at Dallas developed a generic protocol combination methodology. This methodology, called ADAPT (A Dynamically Adaptive Protocol for Transmission) uses an allocation based protocol such as TDMA or TSMA as the base protocol and integrates a contention based protocol such as CSMA/CA into each slot in order to reclaim and reuse bandwidth. This results in a hybrid protocol whose performance resembles its contention component at low load and its allocation component at high load. An in-depth comparison of ADAPT to Collision-Avoidance Time Allocation (CATA) and IEEE 802.11 showed that the overall performance of ADAPT is superior. We also showed how the methodology can support reliable broadcast at the MAC layer, as well as a mix of broadcast and unicast traffic and how it can also be used for performing slot reservations at the MAC layer.

Finally, the University of Texas at Dallas developed the DREAM (Distance Routing Effect Algorithm for Mobility) protocol, one of the two first routing protocols to incorporate GPS location and direction into routing. DREAM uses an energy efficient location dissemination mechanism paired with an on-demand routing of packets in the direction of the destination. The University of California, Los Angeles implemented DREAM in the GloMoSim library and confirmed our results that DREAM is extremely robust to mobility.

The hybrid nature of both the ADAPT and DREAM protocols represent new frameworks for achieving adaptivity to mobility, density, load and other conditions in an ad hoc network. These hybrid protocols capture the "best of both worlds", namely the both the advantages of determistic and probabilistic protocols at the MAC layer, and both the advantages of proactive and reactive (on-demand) routing protocols at the network layer.

The rest of this report is organized as follows. Section 2 gives a statement of the problem studied. Following this, Section 3 s a detailed summary of the major results of this GloMo project. Sections 4 and 5 gives a list of the publications resulting from this work, as well as a list of the scientific personnel who participated in the project, respectively.

2 Problem Statement

The objective of the research in this GloMo project was to develop and test a control channel mechanism for mobile multi-hop radio networks based on the Time-Spread Multiple-Access (TSMA) protocol [8].

Control, or signalling, traffic is an integral part of all networks but is even more ubiquitous in mobile networks as the protocols must also adapt to mobility. Since a mobile multi-hop network does not operate in a centralized manner, mobility in this environment yields an even higher volume of control traffic than in a cellular environment where basestations are fixed. Some examples of control traffic include: link state updates and route discovery, reply and maintenance for the purposes of routing; the establishment and maintenance of multicast routing structures such as trees and meshes; the set-up and maintenance of a hierarchical node structure (i.e., clusterhead election, affiliation and reaffiliation of nodes with clusters); the implementation of a virtual backbone organization; the set-up and maintenance of virtual circuits, and so on. Since wireless communication is error prone, it is imperative that the network is able to recover from packet losses rapidly. As well, in a military scenario, an urgent situation such as an attack can generate extremely high traffic volume (load) on both the control and the data channel. The success of the response, or the mission, may depend on obtaining throughput with guaranteed delay, the ability to support traffic priority in the control channel which in turn is reflected by the performance of the data channel. Thus, the reliability and survivability of the control channel under high load and under mobility is an important issue in mobile multi-hop radio networks.

Very important, yet often overlooked, is the fact that the control channel protocol itself must be mobility transparent yet guarantee delay at high load fairly to all nodes. Probabilistic protocols, such as Aloha and IEEE 802.11, while mobility transparent cannot guarantee access to the channel within a deterministic time bound, and are unstable at high load. As a result, these protocols cannot support priority traffic classes nor any notion of fairness. TDMA is an obvious solution that satisfies both requirements but because of the lack of spatial reuse, the network throughput is unacceptably low. Spatial reuse TDMA protocols reassign time slots as topology/density changes. The achilles heel of these protocols is that they rely on another protocol in order to recompute the TDMA schedules which requires the exchange of control information on the control channel creating an unresolvable "chicken and egg" problem. While satisfactory at low network load and mobility rate, spatial reuse TDMA protocols lose both mobility transparency and guaranteed delay bounds when mobility is high. In summary, current control/signalling channels in mobile multi-hop networks cannot guarantee the delivery of control information, or delivery deadlines, making the network operation potentially inherently unstable as topology changes.

The Time-Spread Multiple-Access (TSMA) protocol unifies the mobility transparency of probabilistic protocols with the guaranteed delay of deterministic protocols. TSMA used for the realization of the control channel has the following unique properties:

- TSMA provides guaranteed channel access to each node within a deterministically bounded access delay, unlike probabilistic protocols.
- TSMA does not require the reassignment of time slots as topology changes, i.e., it is mobility transparent. A TSMA transmission schedule is permanently assigned to each node.
- In TSMA, the delay bound grows only logarithmically with network size, rather than linearly as in TDMA, providing excellent spatial reuse in the network.
- TSMA makes it possible to incorporate the feedback information within the protocol itself, thus making the protocol its own feedback channel.

These properties combine to make TSMA an ideal basis for the implementation of a reliable control channel supporting a quality of service guarantee in a mobile multi-hop radio network.

3 Summary of Important Results

3.1 Demonstration of TSMA as a Control Channel Mechanism in MMWN

Multimedia over Mobile Wireless Networks (MMWN) is a modular system of distributed, autonomous, adaptive mechanisms designed to provide, at the link and networks layers, the communications services required to support real-time distributed multimedia applications in large, mobile multi-hop wireless networks [18]. Two high-fidelity simulators of MMWN using emulated radios were developed by our subcontractor BBN Technologies: a Maisie (precursor of Parsec [17]) version of MMWN and a CPT (C++ Protocol Toolkit [12]) version of MMWN. Even though the Maisie version had more functionality of the system implemented, BBN elected to integrate TSMA into the CPT version of MMWN since the CPT code can be loaded into embedded network hardware enabling the potential to run TSMA as part of a radio testbed.

3.1.1 Improving TSMA Performance using ACKs

TSMA was originally designed for the transmission of a control packet from a node to all of its neighbours (broadcast), such as "hello" packets for neighbour discovery, or link state routing packets. Since some control packets only need to be transmitted to a single neighbour (unicast), e.g., virtual circuit set-up and tear-down packets, we were interested to improve the TSMA protocol for this class of packets.

We achieved an improvement of both throughput and delay by developing an acknowledgement scheme for TSMA to support unicast packets. This scheme essentially extends the length of each slot of the TSMA transmission schedule in order to permit the destination of a unicast packet to return an acknowledgement in the same slot. The overhead associated with this modification is the length of the acknowledgement packet, the ramp up and turnaround time for the radios, the maximum link propagation delay as well as the additional time to process the acknowledgement.

We showed analytically that the delay for unicast packets was significantly reduced by this acknowledgement scheme (on average, half the delay). As well, we proved the correctness of the scheme by showing that the acknowledgement sent by the destination cannot collide at the source with any other acknowledgement packet) [14, 15].

The acknowledgement scheme was implemented in MMWN and experimental results show that acknowledgments considerably increase the number of successful virtual circuit set-ups per second and lower delay at medium loads. As well, acknowledgements considerably increase the number of unicast packets delivered per second. In contrast to the virtual circuit set-up delay, the unicast packet delay showed a marked improvement in MMWN with the acknowledgement scheme [15]. As a consequence, a mix of broadcast and unicast control traffic shows improved performance since a frame can begin on any slot boundary.

3.1.2 A Comparison of TSMA and CSMA in MMWN

All of the GloMo simulation environments are high fidelity, meaning they simulate protocols at several layers in the protocol stack with great accuracy. While such an accurate simulation approximates a real system very well, with our current technology these simulations run slowly because of the level of detail modelled. Thus generally only few nodes are instantiated in a simulation run. Usually, the number is at most fifty nodes and even then, for repeating experiments to obtain statistically significant results usually fewer nodes are used. Only recently, has UCLA's GloMoSim [1] been able to simulate a larger number of nodes through the use of parallel processing and the techniques of node and layer aggregation.

Other commonalities that these GloMo simulation environments share include that in most, no separate control channel is modelled, and no means to control the topology (and therefore the density in the network) is provided. This is true of BBN's MMWN, SAIC's SEAM-LSS [20], Rockwell Collins's Soldier Phone [22], ITT's HMT (RAVEN) [19] project and many more.

The absence of a separate control channel in the model is overcome in some systems by taking a time interval, dividing it into two, and transmitting control packets for one part of the interval and transmitting data packets in the other part of the interval. In other systems, such as MMWN, control information is transmitted in the same manner as a data packet, i.e., using the MAC protocol. This can present a challenge for the collection of statistics as, for example, there may only be a single queue for arriving packets (data and control).

For TSMA, the number of nodes and the density of the network are critical parameters. TSMA excels in large, sparse networks. This is evident by examining the TSMA design equations. In order to compute the transmission schedules, we must find a prime number q and an integer k such that the non-covering condition $q \geq kD + 1$ and the uniqueness condition $q^{k+1} \geq N$ are satisfied. In these equations, D is an upper bound on the maximum node degree in the network, and N is the number of nodes in the network. The resulting transmission schedule will have length q^2. Since no benefit is obtained over simple TDMA if $q^2 > N$ we are interested in finding transmission schedules of length $q^2 \ll N$.

To determine the effectiveness of a control channel protocol, we must measure its impact as a server to control channel operations. For example, are we able to set up more virtual circuits when TSMA is used as the control channel protocol as compared to using another protocol on the control channel? While the conventional measures of throughput and delay do not demonstrate the effectiveness of the control channel, improving the throughput of the control channel protocol and reducing its delay can contribute to its effectiveness as a server.

Thus, the simulation plan was to evaluate the effectiveness of TSMA as a control channel protocol within the context of MMWN and to compare it to the existing CSMA MAC protocol. An interesting study would be to determine the set of control protocols that best utilize TSMA characteristics. Due to the limited functionality of the CPT version of MMWN (hierarchical clustering and routing functions were not implemented) the only experiments possible were to study the dependence of the virtual circuit set-up latency and the virtual circuit set-up loss rate on various parameters.

Before these experiments to compare TSMA with CSMA could be run, we first needed to estimate the average and maximum node degree that resulted from the radio propagation and mobility models used in MMWN in order that appropriate TSMA parameters could be selected. The MMWN simulation environment uses randomly generated network topologies. To determine the average and standard deviation of the network degree, experiments were run in which the nodes transmit at the minimum power necessary to keep the network connected. For a network of fifty nodes connected for the duration of the experiment, the maximum degree was surprisingly high, with an average around twelve with a standard deviation of four [15]. Since the TSMA transmission schedule length is $O(\frac{D^2 \log^2 N}{\log^2 D})$ [8], these unexpectedly high values for the mean and standard deviation of node degree meant that no TSMA parameters could be found that satisfy the design equations for such small networks.

As well, BBN found that experiments on the order of fifty nodes ran for a prohibitively long time, and did not easily permit experimentation with the many parameters of the TSMA protocol and the MMWN network. Due to hardware constraints for experiment repeatability, and budgetary constraints, the parameters used by BBN were a static network with $N = 20$ nodes with a maximum node degree of $D = 8$. This resulted in a transmission schedule of length $q^2 = 121$. This is more than five times longer than a simple TDMA transmission schedule for twenty nodes resulting in throughput and delay statistics at least five times higher than the expected worst case. (TDMA should be, in the worst case, a loose upper bound on both the delay and throughput.) This, in turn, was responsible for the reduced performance of the TSMA protocol as a control channel mechanism in MMWN.

CSMA is the built-in MAC protocol used in MMWN both for the transmission of data and control packets. The comparison of TSMA with CSMA is somewhat subjective as it is difficult to find meaningful methods and metrics to compare such diverse protocols. CSMA is an asynchronous, random access protocol that can utilize variable frame lengths. It provides no delivery guarantees for packets. TSMA is a synchronous (slotted) protocol whose slot size must accommodate the largest packet expected (link state packets in this case). As a result, short packets pay a substantial overhead. TSMA does provide guarantees on both delay and throughput, but the schedule length depends both on the number of nodes in the network and the maximum node degree. In order to best account for these differences, we compute the statistics on a per hop basis. For example, given a virtual circuit of length ℓ, the delay to set up the circuit using a given protocol was divided by ℓ to establish the delay on a per hop basis.

The experiments run by BBN in MMWN on the twenty node randomly generated network used a number of traffic generators at arbitrary locations in the network to generate the virtual circuit requests in a shuffle-periodic manner. The rate of virtual circuit set-up requests from these traffic generators were used to control the offered load to the network. Once a virtual circuit was set up successfully, it was immediately discarded and no data is sent over the circuit [15]. MMWN does not have a separate control channel and only one queue for packet arrivals. Thus extensive redesign of the MMWN architecture, out of the scope of the budget, would have been required in order to model the control channel separately. The results of the experiments showed that the maximum throughput of virtual circuits set-up per second was higher when CSMA was used as the control channel protocol than when TSMA was used. As well, correspondingly lower delays for CSMA were obtained. However, the results are considerably better when the TSMA figures are adjusted by the worst case frame length (that of N for TDMA). For larger N in which schedules of length $q^2 \ll N$ could be found, even better results could be obtained. As well, the queueing problems and loss of link adjacencies that were experienced would also be ameliorated.

3.1.3 Leveraging Autonomous Topology Control in MMWN

Many radios can control the power at which they transmit. Recent protocols have tried to take advantage of power control in the interests of conserving battery life. In BBN's Density- and Asymmetry- Adaptive Wireless Network (DAWN) [13], algorithms to create and maintain a network with desired connectivity characteristics (such as node degree) using power control were developed. DAWN is MMWN extended with a newly developed ATC module, for autonomous topology control. Since the length of the TSMA transmission schedule is critically dependent on the maximum node degree of the network, the ability to control (i.e., reduce) the degree using ATC appears to be a perfect match. A network with low degree is not only useful for TSMA, it has a number of other advantages such as increasing network capacity due to spatial reuse or through the use of shorter frame lengths in synchronous protocols, and less overhead for link state updates for link state routing protocols. Very little time was available to experiment with ATC since this capability in MMWN was only recently available. ATC represents perhaps the most promising avenue of open research for using TSMA in small networks.

A very simple power control heuristic was used in MMWN: when the number of links exceeds a maximum threshold the power is successively dropped until the number of links falls below the threshold or until the minimum transmit power is reached. No attempt was made to keep the network connected. The experiments showed that operating the network with an aggressive TSMA schedule that potentially violates the degree constraints can lead to better performance [15].

This study led to the interesting question of how closely the parameters of TSMA should be engineered to the network. BBN investigated the notion of an aggressive TSMA schedule. This is the use of TSMA schedules in which the TSMA parameters might not match the actual worst case network conditions. An interesting case to consider is engineering the schedule for the *average* node degree rather than the maximum node degree. It would be expected that occasionally the protocol would miss the delay guarantee if temporary dense groups formed, but it is extremely unlikely that this would cause the network to become unstable quickly. Using such aggressive schedules teamed with ATC could be very effective. Further examination of TSMA in MMWN with ATC was recommended by BBN.

3.1.4 Technology Transition

Significant effort was placed into attempting to transition TSMA into other GloMo technologies. Specifically, using TSMA in the RAVEN project and, more intently, in the Rockwell Collins's Soldier Phone, were explored. ASPEN [23] was unwilling to consider changing its protocol. The dual benefits of mobility transparency and guaranteed delay that are offered by TSMA was always enthusiastically embraced. What discouraged its acceptance was the current limitations of both hardware and software of the network size. To achieve significant benefits from TSMA the number of nodes in the network must be on the order of hundreds, or thousands. Furthermore, the network must be relatively sparse. As described in Section 3.2, in simulation work performed by the University of Texas at Dallas where the density of the network could be controlled, TSMA outperformed all the probabilistic protocols under high traffic loads. Thus, as larger networks can be feasibly simulated, built and studied, TSMA together with the added potential of topology control, is a viable protocol.

3.1.5 Summary of TSMA in MMWN

In summary, the effort to demonstrate TSMA as a control channel mechanism in MMWN resulted in the following accomplishments and conclusions:

- A provably correct acknowledgement scheme was designed for TSMA and was implemented in MMWN. Experimental results showed that acknowledgments substantially improved unicast packet throughput and delay, and consequently improvement in a mixed traffic scenario.
- The mean and standard deviation of node degree in randomly generated network topologies was found to be much higher than expected in small networks. TSMA excels in large, sparse networks. Thus, the results of the experiments showed similar performance of TSMA and CSMA when the TSMA frame length was adjusted by the worst case frame length.
- One application of autonomous topology control is for reducing node degree. A network using ATC matched with aggressive TSMA schedules shows considerable promise as a strong solution for smaller networks.

3.2 A Study of TSMA as a MAC Protocol

While TSMA was proposed for use as a protocol on the control channel, it can also be used as a protocol for data transmission, i.e., a MAC (medium access control) layer protocol. The University of Texas at Dallas studied TSMA in the context of a MAC protocol.

The MAC layer was modelled with high fidelity in a simulator implemented in the C++ programming language. The operation of the lower and higher layers was abstracted out in order to permit the instantiation of

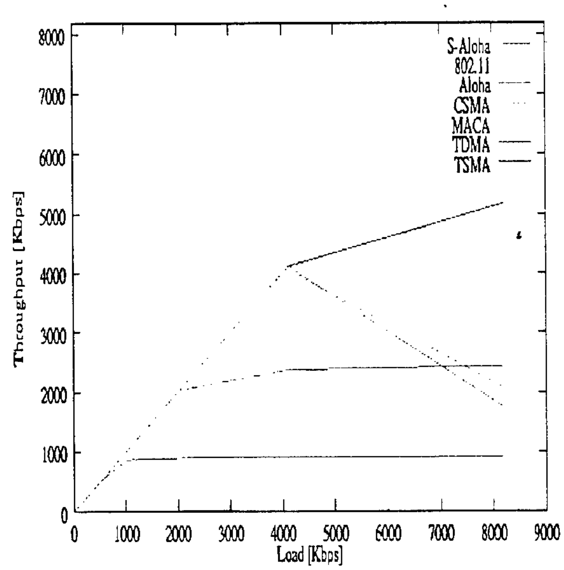

Figure 1: Throughput comparison of TSMA as a MAC protocol.

a larger number of nodes in the simulation then was possible in MMWN. Furthermore, a mobility model was developed that ensured that the network was connected every time the nodes moved. More importantly, the resulting connected network was guaranteed not to exceed a prescribed maximum node degree. Thus the node degree constraint of the TSMA transmission schedule was never violated during simulation. The results of the experiments greatly support the benefits of using ATC in smaller networks.

TSMA was evaluated as a protocol for data transmission (i.e., computed its throughput and delay as a function of load and mobility) and compared it with the several protocols, namely: Aloha, Slotted Aloha, non-persistent CSMA, TDMA, MACA and IEEE 802.11. Figures 1 and 2 are representative of our results. These figures are for relatively small networks of $N = 121$ nodes. The TSMA schedule used the parameters of $q = 11$, $k = 1$ and $D = 10$ resulting in a schedule of length $q^2 = 121$ (exactly equal to a TDMA schedule in this case). The transmission speed of the network was 10 Mbps and a traffic mix was generated using a Poisson arrival process.

The throughput curve shows the typical unstablility of Aloha, which breaks down after 2000 Kbps. TDMA remains stable at all loads, as does CSMA while achieving about twice the throughput of TDMA. The remaining protocols (Slotted Aloha, MACA, IEEE 802.11 and TSMA) begin to diverge at 4000 Kbps with Slotted Aloha and MACA breaking down after this load. Both TMSA and IEEE 802.11 continue to achieve increasing throughput, with TSMA exceeding IEEE 802.11. The delay curve shows that TDMA has the longest delay, followed by Aloha and then CSMA. There is a distinct cross over point between TSMA and IEEE 802.11 at a load of 2800 Kbps. For the load of 2800-4100 Kbps TSMA achieves the same throughput of IEEE 802.11 at lower delay. At loads greater than 4100 Kbps all protocols essentially have infinitely growing queues. Thus in relatively small networks, these results strongly support the benefit topology control make to the use of TSMA.

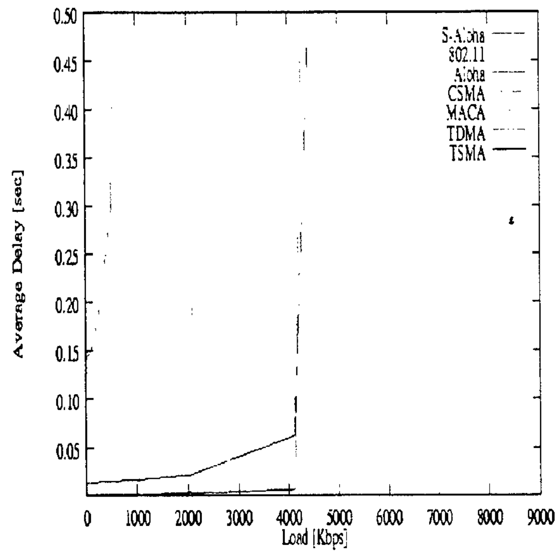

Figure 2: Average delay comparison of TSMA as a MAC protocol.

The strength of TSMA becomes evident at high load, where is can provide a sustained throughput with a guaranteeed delay. This is especially effective for implementing and/or supporting operations (such as broadcast) crucial for delay-sensitive, multimedia applications, such as tele-cooperation (e.g., video conferencing, tele-education, collaborative planning), hypermedia (e.g., web-browsing, web-based transactions), and interactive television (e.g., video-on-demand) [6].

3.2.1 TSMA MAC Protocol Model in the GloMoSim Library

GloMoSim [1] is a scalable simulation environment for wireless network systems being designed using the parallel discrete-event simulation capability provided by Parsec [17] at UCLA. GloMoSim does not have a separate control channel, therefore we provided a model of the TSMA protocol at the MAC layer for inclusion in the GloMoSim library. This model was rewritten twice as the APIs to GloMoSim changed several times. GloMoSim models can also be utilized in SEAM-LSS [20].

Recently, through node aggregation and partitions, UCLA has reported being able to run simulations with a large number of nodes (several thousand). This is achieved through the use of more than one partition, i.e., true parallelism. This feature of GloMoSim is not released with the library as yet since it is still under development and testing.

The University of Texas at Dallas has verified the correctness of the TSMA MAC protocol model in GloMosim, but did not evaluate its performance as a MAC protocol with other MAC protocols in the library. This would be a non-trivial undertaking as first appropriate TSMA parameters must be found given the radio propa-

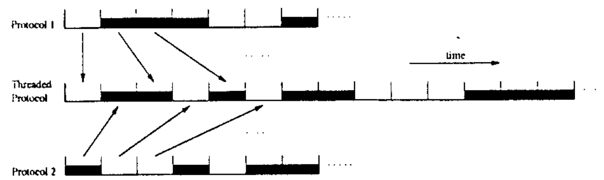

Figure 3: Threading two TSMA protocols together.

gation and mobility models of GloMoSim. It is difficult to access and compute statistics related to node degree. Further, the relationship between a higher layer protocol, such as telnet, and the MAC layer is not yet well understood. This "plug-and-play" notion of protocols in the protocol stack and the interaction of adjacent protocols in the protocol stack is the subject of active research.

3.3 ADAPT: A General Protocol Combination Methodology

Since we were limited to small networks in which to evaluate TSMA we researched new extensions to and variants of TSMA in order to make the protocol viable in the circumstance in which the simulation environment dictated. Such extensions included ideas that take advantage of the presence of neighbour information, how it may be possible exploit the existence of additional control channels, and how TSMA can better use existing radio features such as multiple channels, carrier sensing, and collision detection in order to further increase throughput and reduce delay.

A protocol threading approach was developed to interleave several different TSMA protocol frames on a time sharing basis to obtain a *threaded TSMA*, or T-TSMA, protocol. In other words, in this solution the transmission rights are assigned in different time slots according to different TSMA protocols in a cyclically repeated way, realizing a time sharing that yields a combined protocol with unique properties [11]. An example of interleaving is shown in Figure 3. In general, M protocols can be threaded together with each protocol used in every M^{th} slot. The advantage of this combination is that the component TSMA protocols are optimized for different densities of the topology in a mobile multi-hop network and the threaded protocol can handle all situations without knowing in advance which one will occur. While T-TSMA can eliminate the degree constraint of TSMA, for small networks the resulting T-TSMA schedules were even longer than TSMA schedules.

A variant of TSMA that added the advantages of CDMA was studied. CDMA has the capability to receive a packet even when there are multiple simultaneous transmissions. It also provides a decreased bit error rate and is more resistant to jamming. In TSMA, the multiple reception is modelled by introducing a secondary conflict tolerance. Simulation showed that as the conflict tolerance is increased, both TSMA and Slotted Aloha achieve higher throughput. However, while the throughput curves have a higher maximum, and Slotted Aloha is stable for higher arrival rates, the overall shape of each throughput curve remains the same.

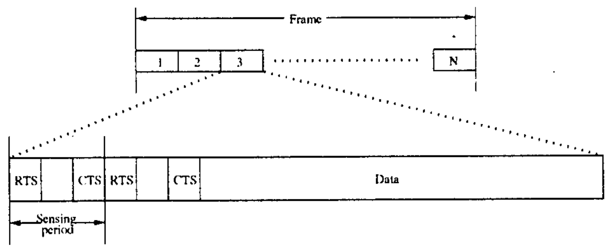

Figure 4: ADAPT: Combining allocation and contention.

In the end, our most successful direction was in developing a new hybrid approach to protocol design. ADAPT is A Dynamically Adaptive Protocol for Transmission that combines, in a novel way, a collision-free allocation based protocol and a contention based protocol while retaining the advantages of each [10]. Our choice for using simple TDMA as the base allocation protocol in this approach is motivated by the fact that it provides the shortest transmission schedule for the "parking lot problem," the situation when every node is in the transmission range of every other (i.e., a fully connected network). Note that any allocation protocol, including TSMA, could be used as the base protocol.

Our choice for using CSMA/CA is motivated by the hidden terminal problem. CSMA/CA attempts to avoid collisions by preceding packets with a RTS/CTS control packet exchange. Figure 4 shows how CSMA/CA is combined with TDMA in ADAPT. For a network of N nodes, we construct a simple TDMA schedules of N slots. A slot is large enough to accommodate the followig. We establish a sensing period in which all nodes j determine where or not a node i is using its assigned slot, s_i. This determination is made by simply listening for any transmissions within the specified sensing period. If node i has a data packet to send in s_i, it can forego listening and immediately contend for the slot using the RTS/CTS exchange of CSMA/CA.

If node i does not have a packet to transmit, then after the sensing period all other nodes will have determined that i is not using s_i. At this time, any node with a packet to transmit will contend for use of this slot using the same RTS/CTS exchange. If any node j successfully performs this exchange, then it is allowed to transmit its data packet in the remaining portion of the slot. Notice that even though the base protocol is full time division, we obtain spatial reuse of any unused dedicated slots.

If there is a collision of nodes contending for use of a slot we manage the contention by using a backoff interval b, initialized to zero at each node. If node i does not use its dedicated slot then other nodes compete for slot i. Whether or not the contention is successful, we increment b (up to some maximum value). This reflects active contention for the slot. Consistent with binary exponential backoff techniques, if a node j contending for a slot i, $i \neq j$, experiences a collision, it will wait a random number r, $1 \leq r \leq 2^b$ of slots before contending for a slot again. The only time we reduce the backoff interval is when a slot i is unused. In this case, b is decremented, reflecting the decrease in contention for the slot.

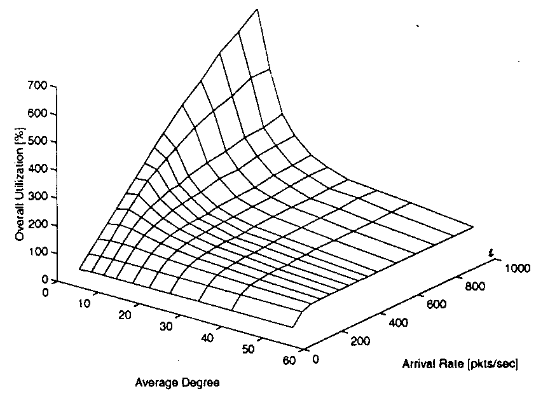

Figure 5: ADAPT channel utilization.

In this way, each node dynamically self-adjusts its contention for slots based on the load. At low loads or density, ADAPT behaves as CSMA/CA with similar performance. As the load or density increases, ADAPT changes its operation into TDMA, where each nodes uses its dedicated slot. In fact, there is still the opportunity for spatial reuse, even at high load. There is very little overhead associated with the combined protocol, namely, the sensing period and the RTS/CTS message exchanges. Furthermore, these adaptations occur independently at each node, according to its mobility, the density of its neighbourhood and the offered load. Thus, ADAPT is not only mobility transparent, but also density and load transparent.

We performed a simulation study to compare the performance of ADAPT to CATA [21] and IEEE 802.11 [9]. Figure 5 shows the channel utilization of the ADAPT protocol. As expected, the channel utilization of ADAPT exceeds the channel capacity in those cases when the nodal degree is relatively sparse, i.e., when the average node degree is relatively low (≤ 10). This increased utilization can be attributed to the ability of ADAPT to reclaim and reuse the increased number of idle TDMA slots via its contention mechanism. As the average node degree and traffic load are increased, the number of idle TDMA slots decreases. Consequently, the contention level for the few remaining idle slots increases, reducing the probability of successful transmission in an unassigned slot. As a result, the channel utilization is highly dependent upon the average node degree. However, even under high traffic loads and nodal degree, ADAPT remains stable (i.e., near full utilization) since every node is guaranteed access to at least one slot per frame.

Figure 6 depicts the average access delay of the ADAPT protocol is also shown as a function of the average node degree and traffic load. As anticipated, the average access delay is monotonically non-decreasing with respect to increasing load and node degree. Nevertheless, the underlying TDMA allocation protocol prevents the access delay from exceeding 1 second which corresponds to the frame length employed.

Both ADAPT and CATA have similar performance when the average node degree is relatively low (≤ 10). However, unlike the ADAPT protocol, CATA does not permanently assign slots to nodes. Consequently, CATA does not provide channel access guarantees, and is subject to instability under more strenuous network conditions.

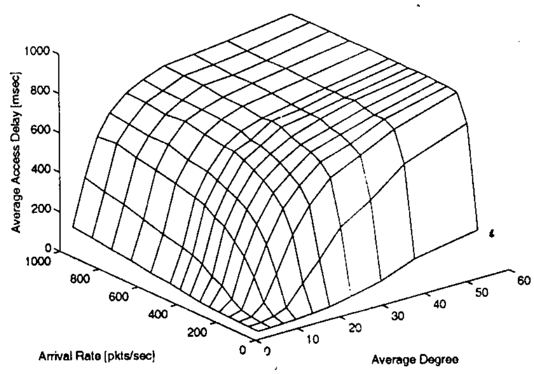

Figure 6: ADAPT average access delay.

In fact, when the average node degree exceeds 30, the CATA protocol is incapable of achieving full utilization at any traffic load.

Since it does not provide any channel access guarantees, the access delay of CATA is unbounded. Thus, as the protocol becomes increasingly unstable at higher traffic loads and nodal degrees, the average access delay begins to increase rapidly. In fact, at the maximum average degree the access delay of CATA is nearly three times that of the ADAPT protocol.

When the network load and nodal degree are low, the 802.11 protocol functions effectively, yet its maximum performance is less than that of both the ADAPT and CATA protocols. However, the overall utilization of the IEEE 802.11 protocol degrades more gradually with increasing nodal degree and traffic load. Moreover, the utilization of the 802.11 protocol remains stable. This can all be attributed to the influence of carrier sensing since this reduces the overall contention level at the expense of increased packet delay.

Compared to the ADAPT and CATA protocols, the access delay of the 802.11 protocol is reduced when the traffic load and nodal degree are low. This is attributed to reduced contention levels caused by the influence of carrier sensing. However, at the higher loads and nodal degrees, the presence of carrier sensing begins to have a negative affect on the measured access delay. In comparison to the CATA protocol, the 802.11 access delay surface is more convex since the access delays are slightly higher for the intermediate values. Moreover, at the highest traffic load and nodal degree, we find that the access delay of 802.11 is about 500 milliseconds more than the equivalent CATA delay.

We were able to extend the idea of ADAPT to develop a hybrid MAC protocol that supports reliable broadcast transmissions in ad hoc networks [7] as well as a combination of point-to-point and multi-point transmission services [16].

3.4 The DREAM Directional Routing Protocol in GloMoSim

DREAM, the Distance Routing Effect Algorithm for Mobility, is a hybrid routing protocol for mobile multi-hop networks built around two novel observations [5]. One, called the distance effect, uses the fact that the greater the distance separating two nodes, the slower they appear to be moving with respect to each other. Accordingly, the location information in routing tables can be updated as a function of the distance separating nodes without compromising the routing accuracy. The second idea is that of triggering the sending of location updates by the moving nodes autonomously, based only on a node's mobility rate. We have shown by detailed simulation that DREAM always delivers more than 80using the recovery procedure. In addition, it minimizes the overhead used for maintaining routes using the two new principles of update message frequency and distance.

The University of California, Los Angeles, has implemented our DREAM routing protocol an example of a location aware routing protocol for ad hoc networks in the GloMoSim library. In experiments comparing DREAM with other location aware routing protocols in the library, DREAM has been found to be very robust in the face of mobility.

The idea that formed the basis of DREAM was also used to develop a protocol for geographic messaging [3], incorporated into a dynamic source routing protocol [4], and used for route selection [2] in mobile multimedia ad hoc networks.

4 List of Publications and Technical Reports

4.1 List of Publications

A list of publications in reverse chronological order:

1. *An Adaptive Generalized Transmission Protocol for Mobile Ad Hoc Networks*, A. D. Myers, V. R. Syrotiuk, and G. Zàruba. Conditionally accepted for publication in the ACM MONET Special Issue on Multipoint Communication in Wireless Mobile Networks, Fall 2000.

2. *An Adaptive Media Access Control (MAC) Protocol for Reliable Broadcast in Wireless Networks*, I. Chlamtac, A. D. Myers, V. R. Syrotiuk, and G. Záruba. In the Proceedings of the IEEE International Conference on Communications (ICC), New Orleans, LA, June 18-22, 2000.

3. *A Performance Comparison of Hybrid and Conventional MAC Protocols for Wireless Networks*, I. Chlamtac, A. Faragó, A. D. Myers, V. R. Syrotiuk, and G. Záruba. In the Proceedings of the IEEE International Vehicular Technology Conference (VTC-Spring), Tokyo, Japan, May 15-18, 2000.

4. *Mobility Transparent Deterministic Broadcast Mechanism for Ad Hoc Networks*, S. Basagni, D. Brushi, and I. Chlamtac. ACM/IEEE Transactions on Networking, vol. 7, no. 6, December 1999.

5. *ADAPT: A Dynamically Self-Adjusting Media Access Control Protocol for Ad Hoc Networks*, I. Chlamtac, A. Faragó, A. D. Myers, V. R. Syrotiuk, and G. Záruba. Proceedings of the IEEE Global Telecommunications Conference (GLOBECOM), Rio De Janeiro, Brazil, pp. 11-15, December 5-9, 1999.

6. *Route Selection in Mobile Multimedia Ad Hoc Networks*, S. Basagni, I. Chlamtac, A. Faragó, V. R. Syrotiuk, and R. Talebi. Proceedings of the IEEE International Workshpp on Mobile Multimedia Communications (MOMUC), pp. 97-104, San Diego, CA, November 15-17 1999.

7. *A Distributed Algorithm for Finding a Maximal Weighted Independent Set in Wireless Networks*, S. Basagni. Proceedings of the IASTED International Conference on Parallel and Distributed Computing and Systems (PDCS), vol. 1, pp. 517-522, Cambridge, MA, November 3-5 1999.

8. *Dynamic Source Routing for Ad Hoc Networks Using the Global Positioning System*, S. Basagni, I. Chlamtac, and V. R. Syrotiuk. Proceedings of the IEEE Wireless Communications and Networking Conference (WCNC), New Orleans, LA, September 21–24, 1999.

9. *Geographic Messaging in Wireless Ad Hoc Networks*, S. Basagni, I. Chlamtac, and V. R. Syrotiuk. Proceedings of the IEEE International Vehicular Technology Conference (VTC), vol. 3, pp. 1957-1961, Houston, TX, May 16-20, 1999.

10. *Logarithmic Lower Bound for Time-Spread Multiple-Access (TSMA) Protocols*, S. Basagni and D. Bruschi. ACM/URSI/Baltzer Journal on Wireless Networks, 1999.

11. *Mobility-Independent Flooding for Real-Time Multimedia Applications in Ad Hoc Networks*, S. Basagni, A. D. Myers, and V. R. Syrotiuk. Proceedings of the IEEE Emerging Technologies Symposium on Wireless Communications and Systems, Richardson, TX, April 12-15, 1999.

12. *Virtual Path Network Topology Optimization Using Random Graphs*, A. Faragó, I. Chlamtac, and S. Basagni. Proceedings of IEEE Conference on Computer Communications (INFOCOM), vol. 2, pp. 491-496, New York, NY, March 21-25, 1999.

13. *A Distance Routing Effect Algorithm for Mobility (DREAM)*, S. Basagni, I. Chlamtac, V. R. Syrotiuk, and B. A. Woodward. Proceedings of the ACM/IEEE International Conference on Mobile Computing and Networking (MobiCom), pp. 76-84, Dallas, TX, October 25-30, 1998.

14. *Broadcast in Peer-to-Peer Networks*, S. Basagni and I. Chlamtac. Proceedings of the IASTED International Conference European Parallel and Distributed Systems (Euro-PDS), pp. 117-122, Vienna, Austria, July 3-5, 1998.

4.2 List of Technical Reports

A list of technical reports in reverse chronological order:

1. *A Performance Comparison of Hybrid and Conventional MAC Protocols for Wireless Networks*, I. Chlamtac, A. Faragó, A. D. Myers, V. R. Syrotiuk, and G. Záruba. Technical Report UTD/CS-03-00, Department of Computer Science, The University of Texas at Dallas, February 2000.

2. *An Adaptive Generalized Transmission Protocol for Mobile Ad Hoc Networks*, A. D. Myers, V. R. Syrotiuk, and G. Záruba. Technical Report UTD/CS-02-00, Department of Computer Science, The University of Texas at Dallas, February 2000.

3. *An Adaptive MAC Protocol with Integrated Quality of Service Support for Mobile Ad Hoc Networks*, A. D. Myers, V. R. Syrotiuk, and G. Záruba. Technical Report UTD/CS-01-00, Department of Computer Science, The University of Texas at Dallas, January 2000.

4. *ADAPT: A Dynamically Self-Adjusting Media Access Control Protocol for Ad Hoc Networks*, I. Chlamtac, A. Faragó, A. D. Myers, V. R. Syrotiuk, and G. Záruba. Technical Report UTD/CS-02-99, Department of Computer Science, The University of Texas at Dallas, January 2000.

5. *An Adaptive Medium Access Control (MAC) Protocol for Reliable Broadcast in Wireless Networks*, I. Chlamtac, A. D. Myers, V. R. Syrotiuk, and G. Záruba. Technical Report UTD/CS-04-99, Department of Computer Science, The University of Texas at Dallas, April 1999.

5 List of Participating Scientific Personnel

From the University of Texas at Dallas: Imrich Chlamtac, Distinguished Chair Professor of Telecommunications; Violet R. Syrotiuk, Assistant Professor; Andras Faragó, Professor; Stefano Basagni, Assistant Professor; Andrew Myers, earned M.S. in Computer Science; Gergely Záruba, Ph.D. student.

From BBN: Dr. Isidro Castiñeyra, Dr. Ram Ramanathan, Dr. Gregory Lauer, Dr. James P.G. Sterbenz, David Li, Wenyi Zhou, Rajesh Krishnan.

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